MICROSTRIP-TO-WAVEGUIDE POWER COMBINER FOR RADIO FREQUENCY POWER COMBINING

Related Application

This application is based upon prior filed copending provisional application Serial No. 60/374,712 filed April 23, 2002.

Field of the Invention

This invention relates to power combining radio frequency signals, and more particularly, this invention relates to a power combining network for combining radio frequency signals using microstrip and waveguide circuits.

Background of the Invention

Power combining techniques for radio frequency signals, including millimeter wavelength signals, have been accomplished in either a waveguide circuit or in a microstrip circuit. For example, prior art waveguide combining has been accomplished by feeding two or more signals in phase into a waveguide combiner. Although this type of power combining is efficient, the summing network is generally bulky and requires very high precision components. Microstrip power combining circuits have been accomplished by summing signals using a hybrid combiner circuit or a Wilkinson power summer circuit as known to those skilled in the art. This type of power combining

circuit is more simple to implement in practice, but generally has higher losses.

FIG. 1 illustrates a typical waveguide combiner **20**, widely available in the industry, and traditionally used to combine radio frequency signals from two sources of RF power. The combiner **20** can be formed from different materials as known to those skilled in the art, and generally has two input ports **22** that are bolted or fastened by other techniques to respective waveguide sources. The signals combine and are summed at the output port **24**. This combiner **20** provides a reliable method of adding radio frequency energy, but requires careful phase matching of two radio frequency inputs and precisely control over the length of the two waveguide sides **26**. The precision requirements for this waveguide and the requirement for a metal coating on the inside surface of the waveguide to achieve low losses results in relatively expensive devices. Also, this waveguide combiner is usually bulky, as illustrated, and occupies a significant amount of space.

FIGS. 2-4 show typical microstrip power combiners formed from microstrip transmission lines. These type of combiners are widely used in the industry for combining radio frequency power in microstrip circuits. There are primarily two types of microstrip combiners, using Wilkinson and hybrid circuits, as shown in the schematic circuit diagrams of FIGS. 2 and 3, respectively. The Wilkinson combiner **30** shown in FIG. 2 is a reflective combiner and includes two inputs **32**, an output **34**, and the Wilkinson circuit **36** that has a resistor for circuit balance as known to those skilled in the art. The hybrid combiner **40** shown in FIG. 3 is absorptive and includes two inputs **42**, an

output **44**, and load resistor **46**, forming a four port hybrid combiner. FIG. 4 illustrates a plan view showing the microstrip transmission lines **48** forming the circuit. In the hybrid combiner **40**, the load resistor **46** absorbs any reflected energy because of mismatch. Typically, the three decibel (dB) Wilkinson combiner **30** results in 0.5 dB loss, while the hybrid combiner **40** results in 0.8 dB losses. These combiners provide a reliable method of RF energy summing and can be used in a very small space.

Other examples of various types of combiners and different RF coupling systems are disclosed in U.S. Patent Nos. 4,761,654; 4,825,175; 4,870,375; 4,943,809; 5,136,304; 5,214,394; and 5,329,248.

As is also known to those skilled in the art, in a waveguide-to-coaxial line connector, a maximum energy field is in the center of the waveguide. An extension of a center conductor can be located at the point of a maximum energy field and act as an antenna to couple energy from a coaxial line into a waveguide. Coupling from a coaxial line to a waveguide could be achieved by using a loop, which couples two magnetic fields. In a prior art waveguide circuit using stripline or microstrip, the center conductor of a stripline can be extended into a waveguide forming a probe (or launcher). By increasing the width of a center conductor at the end of a probe, bandwidth can be improved. Also, the conductor and substrate of a microstrip circuit, but not a ground plane, can be extended directly into a guide.

In a prior art coaxial line circuit using a microstrip connection, the center conductor of a coaxial line can be pressed against or soldered to a conductor of a microstrip. The outer conductor of a

coaxial line can be grounded to a microstrip ground plane. The microstrip substrate thickness could be as little as 0.010 inch for frequencies above 15 GHz, and usually requires decreasing the diameter of the coaxial line. In yet other types of systems, various directional couplers have waveguides that are located side-by-side or parallel to each other, or crossing each other. Stripline and microstrip couplers can have main transmission lines in close proximity to secondary lines. Although these examples can provide some power combining and coupling, they are not useful for combining two or more sources of radio frequency energy in a microstrip-to-waveguide transition with low losses or small "real estate" at an efficient rate at low power loss.

Summary of the Invention

It is therefore an object of the present invention to provide a microstrip-to-waveguide and a coaxial-to-waveguide power combiners that overcome the disadvantages of the prior art power combiners identified above and has low losses, small "real estate," and is power efficient.

The present invention is advantageous and power combines radio frequency signals using a combination of microstrip and waveguide circuit techniques that result in very low losses. The combining network is compact and can be used at a low cost. In the present invention, two or more sources of radio frequency energy can be combined in a microstrip-to-waveguide transition resulting in low losses. Also, two or more sources of radio frequency energy in a microstrip-to-waveguide transition are combined and are not as sensitive to phase mismatch between the radio frequency sources as other power combine methods. The

power combining is achieved efficiently at a low cost and is implemented in compact spaces. The method and apparatus of the present invention allows radio frequency power combining that can be implemented at any frequency where energy can be transferred over a waveguide.

In accordance with one aspect of the present invention, the microstrip-to-waveguide power combiner includes a dielectric substrate and at least two microstrip transmission lines formed thereon in which amplified radio frequency signals are transmitted. The at least two microstrip transmission lines terminate in microstrip launchers (probes) at a microstrip-to-waveguide transition. A waveguide opening is positioned at the transition. The waveguide back-short is positioned opposite the waveguide opening at the transition. Isolation/ground vias are formed within the dielectric substrate and positioned around the transition to isolate the transition and provide a ground well. The radio frequency signals can be millimeter wavelength radio frequency signals.

In yet another aspect of the present invention, a metallic plate supports the dielectric substrate. A back-short cavity is formed within the metallic plate at the transition to form the waveguide back-short. This back-short cavity has a depth ranging from about 25 to about 60 mils and its overall dimensions are about the size of the waveguide opening. The back-short is positioned for reflecting energy into the waveguide opening.

In yet another aspect of the present invention, each microstrip transmission line has a power amplifier associated therewith and supported by the dielectric substrate. The phase of each power amplifier is adjusted based on the location of

microstrip launchers or probes at the transition. The number of microstrip launchers, in one aspect of the invention, can be either two or four and the respective phase of the power amplifiers is 180 degrees apart for two opposed microstrip launchers or 90 degrees apart for four microstrip launchers when positioned at 90 degree angles to each other. The power amplifiers comprise microwave monolithic integrated circuits (MMIC) in one aspect of the invention.

A method aspect of the present invention is also disclosed for power combining radio frequency signals by combining two or more amplified radio frequency signals at a microstrip-to-waveguide transition that is formed from a dielectric substrate having at least two microstrip transmission lines thereon in which radio frequency signals are transmitted. The transition includes a waveguide opening and a waveguide back-short positioned opposite the waveguide opening. Each microstrip transmission line has a microstrip launcher or probe extending into the transition. Isolation vias are formed within the dielectric substrate around the transition and isolate the transition and provide a ground well around the transition.

Brief Description of the Drawings

Other objects, features and advantages of the present invention will become apparent from the detailed description of the invention which follows, when considered in light of the accompanying drawings in which:

FIG. 1 is an isometric view of a prior art waveguide combiner.

FIG. 2 is a schematic circuit diagram of a prior art microstrip power combiner as a Wilkinson combiner.

FIG. 3 is a schematic circuit diagram showing a prior art, four-port hybrid power combiner.

FIG. 4 is a plan view of the four-port hybrid power combiner shown in FIG. 3.

FIGS. 4A and 4B are respective side elevation and front views of a coaxial-to-waveguide transition of the general type that could be used as modified by the present invention for power combining.

FIG. 5 is a block diagram of a microstrip-to-waveguide power combiner of the present invention and showing two sources of radio frequency energy.

FIG. 6 is another block diagram of a microstrip-to-waveguide combiner of the present invention and showing four sources of radio frequency energy.

FIG. 7 is a plan view of a power combiner using two sources of radio frequency energy, such as shown in FIG. 5.

FIG. 8A is a fragmentary, side sectional view of the power combiner shown in FIG. 7.

FIG. 8B is an exploded isometric view of a microstrip-to-waveguide transition of the general type that can be used in the present invention.

FIGS. 8C and 8D are respective fragmentary top and side elevation views of a microstrip-to-waveguide transition of the type as shown in FIG. 8B.

FIG. 9 is a fragmentary plan view of a microstrip-to-waveguide power combiner having four sources of radio frequency energy and showing a microstrip-to-waveguide transition and four microstrip launchers.

FIG. 10 is a fragmentary, side sectional view of the microstrip-to-waveguide transition of FIG. 9.

FIG. 11 is a plan view of another microstrip-to-waveguide transition similar to FIG. 9, but showing a configuration where the microstrip launchers are positioned 90 degrees relative to each other.

FIGS. 11A and 11B are respective side elevation and front views of a coaxial-to-waveguide transition and power combiner.

FIG. 12 is a graph illustrating a microstrip-to-waveguide combiner return loss of the present invention as a non-limiting example.

FIG. 13 is another graph illustrating a power combiner sensitivity to radio frequency source phase mismatch, in accordance with one example of the present invention.

Detailed Description of the Preferred Embodiments

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

The present invention is advantageous and power combines radio frequency signals using a combination of microstrip and waveguide or coax and waveguide techniques that result in very low losses. The power combining network of the present invention is extremely compact and can be used at a very low cost.

In the present invention, two or more sources of radio frequency energy can be combined in a microstrip-to-waveguide or coax-to-waveguide transitions resulting in extremely low losses. Also, two or more sources of radio frequency energy are combined in microstrip-to-waveguide transition and are not as sensitive to phase mismatch between the radio frequency sources as other methods of power combining. The power combining is achieved efficiently at a low cost and is implemented in compact spaces. The method and apparatus of the present invention allow RF power combining that can be implemented at any frequency where energy can be transferred over a waveguide.

FIGS. 4A and 4B illustrate respective side and front views of a coaxal-to-waveguide transition **49'** of the general type that can be modified and used with the present invention, including a coaxial cable support body **49a**, formed back short **49b**, a single launch probe **49c** and coaxial connector **49d**. Through holes (or screw holes) **49e** provide means for receiving screws or other attachment fasteners (not shown) as known to those skilled in the art. This type of transition is widely used in the industry and has a 0.25 to 0.5 dB loss.

FIG. 5 illustrates a block diagram of a microstrip-to-waveguide power combiner **50** of the present invention showing two sources of radio frequency energy. As illustrated, a microstrip transmission line input **52** enters a high power amplifier **54** that can be formed as a microwave monolithic integrated circuit (MMIC). The signal passes over a microstrip transmission line to a microstrip rat race power divider **56**, having a 50 ohm terminating resistor **56a** as a value typically chosen by

many skilled in the art as a complement for 50 ohm microstrip transmission lines. A zero degree (0°) phase shift circuit **57** and a 180 degree phase shift circuit **58** are provided in one microstrip transmission line **60** that extends from the power divider **56** to another high power amplifier **62**. The other microstrip transmission line **64** extends from the power divider into another high power amplifier **66** to a microstrip-to-waveguide transition **68** of the present invention and into a summed output **70**.

FIG. 6 is another block diagram of a microstrip-to-waveguide power combiner **72** similar to FIG. 5, but instead showing four sources of radio frequency energy with respective 90 degree, 180 degree and 270 degree phase shift circuits **74, 76, 78** associated with microstrip transmission lines and high power amplifiers **80** that extend into the microstrip-to-waveguide transition **82** of the present invention. A summed output **84** is illustrated. Power is combined with no additional losses other than normal transition loss, usually resulting in about 0.25 to about 0.3 decibel (dB) loss. The present invention can achieve the same outcome as a waveguide combiner using extremely low losses, but requires no external waveguide combiner. This is advantageous where real estate is an issue.

FIGS. 7 and 8A are respective plan and fragmentary side elevation views of a power amplifier, such as shown in FIG. 5. The power amplifiers **54, 62, 66** are illustrated as preferably formed as microwave monolithic integrated circuits (MMIC) and connected to the respective microstrip transmission lines **60, 64**. As illustrated, a dielectric substrate **90** has the at least two microstrip transmission lines **60, 64** formed

thereon in which radio frequency signals are transmitted. These microstrip transmission lines **60, 64** terminate in opposed microstrip launchers **92**, also referred to as probes, at the microstrip-to-waveguide transition **68** (shown in dashed line). The dielectric substrate **90** can be formed from a ceramic substrate or other similar soft board material, including alumina, as known to those skilled in the art.

A metal base plate **94**, such as formed from aluminum or other similar material, supports the dielectric substrate, and may include ground layer **94a** interposed between the dielectric and metal plate. A waveguide back-short **96** is positioned opposite a waveguide opening **98**. Both are positioned at the transition **68**. The waveguide opening is formed in a waveguide support plate or top metal cover as illustrated at **99** or other structure as known to those skilled in the art. The waveguide opening **98** forms a waveguide launch **98a**. A back-short cavity **100** is formed within the metal plate **94** at the transition to form the waveguide back-short **96**. This back-short cavity **100** has a depth ranging from about 25 to about 60 mils and is positioned for reflecting energy into the waveguide opening. The waveguide back-short is dimensioned about the size of the transition in one aspect of the present invention.

FIG. 8A shows the probe or microstrip launcher **92** positioned relative to the microstrip opening **98** and formed waveguide launch **98a**. As illustrated in FIGS. 7 and 9, isolation/ground vias **102** are formed in at least the dielectric substrate **90** and around the transition **68** to isolate the transition and form a well around the transition.

As illustrated, the power amplifiers **54, 62, 66** are formed as MMIC chips or other amplifiers and associated with respective microstrip transmission lines. The power amplifiers have a phase that is adjusted based on the location of microstrip launchers (probes) **92** at the transition **68**. For example, in the example of FIGS. 7 and 8 as shown in the schematic circuit diagram of FIG. 5, two microstrip launchers **92** are opposed to each other, i.e., positioned 180 degrees apart, and the power amplifiers are phase adjusted for 180 degrees.

FIG. 8B illustrates an exploded isometric view of a microstrip-to-waveguide transition with a single microstrip transmission line **120** forming a probe **122**. This type of transition as modified can be used for the present invention and is illustrated for explanation. Similar elements as in the previously described elements will continue with similar reference numerals for purposes of clarity. The back short **96** is illustrated within the metal base plate **94** and forms a cavity for the air or dielectric material **96a** as part of the "cut-out" opening **90a** within the ceramic or other dielectric material **90**. A waveguide opening **98** is formed in the top metal cover **99** and includes screw holes **99a** for receiving screws or other fasteners for fastening the top metal cover, ceramic (or other dielectric material) and base metal plate together in one integral piece. The ground vias **102** are illustrated as formed around the "cut-out" **90a** where the "probe" or microstrip launchers **122** extend thereon. Electronic or MMIC components **122** are shown mounted on the ceramic or other dielectric material and are operable with the microstrip transmission line **120** and other components.

FIGS. 8C and 8D illustrate respective top and side elevation views of a waveguide-to-microstrip transition such as the type shown in FIG. 8D to show greater details of its construction, and showing a 50 ohm microstrip transmission line **120** and the flange holes **94b** formed in the aluminum base plate **94** and the ground layer **94a** supported under the ceramic or other dielectric material **90**. In one aspect of the present invention, the dielectric material is formed as a 10 mil alumina 99.9% with k=9.9. The ground vias are shown in a semi-circle, but in the preferred aspect of the present invention such as shown in FIGS. 5-7 and 9-11, the ground vias circumferentially extend around the back short.

For purposes of description, various dimensions are set forth only as representative capital letters shown in FIGS. 8C and 8D are examples of dimensions.

A ≅ 0.14
B ≅ 0.006
C ≅ 0.010
D ≅ 0.04
E ≅ 0.32
F ≅ 0.075
G preferred not to exceed ≅ 0.070
H ≅ 0.080
I ≅ 0.140
J ≅ 0.063

Although dimensions can vary, these are only one example of the type of dimensions that could be used for microstrip-to-waveguide transition.

FIGS. 9 and 10 show another example of a power combiner of the present invention, but showing four microstrip launchers having different phase differences as associated with respective power amplifiers (not shown in the figures) in the type of

circuit such as shown in FIG. 6. The power combiners shown in FIGS. 9 and 10 have a similar structure using the dielectric substrate and back-short construction, such that similar reference numerals correspond to similar elements. One difference between the different constructions is that four microstrip launchers or probes are used as illustrated in FIGS. 9 and 10.

FIG. 11 is another example showing the microstrip launchers positioned 90 degrees apart from each other such that respective power amplifiers would be phased 90 degrees apart for the four microstrip launchers, as illustrated.

FIGS. 11A and 11B are respective side and front views of a coaxial-to-waveguide 2:1 power combiner with elements similar to those shown in FIGS. 4A and 4B. Two launch probes **49c** are opposed to each other. Otherwise, similar elements are used as before, except modified for power combining as would be suggested by those skilled in the art.

In operation, the back-short **96** has the formed cavity **100** where energy is reflected and exits from its opposite end into a waveguide. The isolation vias **102** help in the reflection of energy. The depth of the back-short, in one aspect, is about 25 to about 60 mils deep, but its depth could be a function of many parameters, including the dielectric constant of the dielectric material **90** (or soft board) and a function of the bandwidth and/or what a designer and one skilled in the art is attempting to achieve. The back-short **96** is typically about the size of the transition **68** and can be on the bottom or on top. If a designer is trying to transmit energy off the bottom, the back-short could be placed on top (basically upside down).

If energy is propagated up into a waveguide, then the back-short is placed on the bottom as illustrated.

FIG. 12 is a graph of the predicted (using electromagnetic simulation) return loss for a 2:1 ka-band power combiner as set forth above. This graph illustrates that the combiner bandwidth (return loss less than -20 decibels) is well over 30%, which is broad for this frequency.

FIG. 13 illustrates a graph of the power combiner gain and transition loss versus phase mismatch between two radio frequency sources. This graph illustrates that the total transition and power combiner losses is under 0.25 decibels with perfect phasing and degrades to about 0.5 decibel loss with +/-30 degree phase mismatch. The typical microstrip-to-waveguide transition losses, without power combining, are about 0.25 decibels to about 0.5 decibels. Therefore, the power combining can be performed in accordance with the present invention with no additional losses.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that the modifications and embodiments are intended to be included within the scope of the dependent claims.